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Particle aggregation in microgravity: Informal experiments on the International Space Station

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Abstract–We conducted experiments in space to investigate the aggregation of millimeter- and submillimeter-sized particles in microgravity, an important early step in planet formation. Particulate materials included salt (NaCl), sugar (sucrose), coffee, mica, ice, Bjurböle chondrules, ordinary and carbonaceous chondrite meteorite fragments, and acrylic and glass beads, all triply confined in clear plastic containers. Angular submillimeter particles rapidly and spontaneously formed clusters strong enough to survive turbulence in a protoplanetary nebula. Smaller particles generally aggregated more strongly and quickly than larger ones. We observed only a weak dependence of aggregation time on particle number density. We observed no strong dependence on composition. Round, smooth particles aggregated weakly or not at all. In a mixture of particle types, some phases aggregated more readily than others, creating selection effects that controlled the composition of the growing clumps. The physical process of aggregation appears to be electrostatic in nature.

INTRODUCTION

A crucial step in planet formation is the growth of solid bodies in the millimeter to meter size range: too large to condense directly from the gas phase and too small to interact strongly through mutual gravitation. The widespread existence of planets demonstrates that some growth mechanism operated in that size regime, but the process is not well understood. Whatever it was, it worked despite nebular turbulence (e.g., Weidenschilling and Cuzzi 1993; Sekiya 1998; Cuzzi et al. 2001; Weidenschilling 2010) that was probably strong enough to disrupt small-scale gravitational collapse via the Goldreich and Ward (1973) mechanism and to break dust structures held together by weak surface forces. Work on this topic (reviewed by Beckwith et al. 2000; Cuzzi and Weidenschilling 2006; Dominik et al. 2007; Blum and Wurm 2008) has included the sticking properties of ice and frost (e.g., Supulver et al. 1995, 1997; Bridges et al. 1996), silicate dust in microgravity environments (e.g., Wurm and Blum 1998; Blum and Wurm 2000; Blum et al. 2000; Marshall and Cuzzi 2001; Wurm et al. 2001; Marshall et al. 2005; Güttler et al. 2010; Weidling et al. 2012; and references therein), and numerically modeled magnetic particles (e.g., Nuth and Wilkinson 1995; Dominik and Nübold 2002; Wang et al. 2010).

Here, we present the results of particle aggregation experiments carried out in microgravity on board the International Space Station (ISS). Despite their simplicity, these experiments illustrated the behavior of millimeter- and submillimeter-sized particles in low-density, low-viscosity gas (air) without the influence of gravity, conditions that are difficult to replicate on Earth for more than a few seconds. We found complex and often counterintuitive effects related to particle size, number density, composition, shape, and surface texture, as well as evidence that may help identify the physical mechanism that underlies the observed behavior. Because of the unsophisticated nature of the experiments it describes, this report is intended primarily to inform more formal and realistic future investigations of weightless particle aggregation.

EXPERIMENTS

One of us (D.R.P.) conducted simple microgravity experiments in off-duty time on the ISS during Expedition 6, Expedition 30, and the docked phase of Space Shuttle mission STS-126. The investigations used materials that were either freely available on board the ISS or carried as part of the crew's limited personal kit.

Studying small particles in a human-operated spacecraft poses logistical challenges. Without gravity, airborne particulates can easily disperse on ventilation currents. They may find their way into crewmembers' eyes or lungs, creating potentially serious medical problems. Mitigating these risks requires at least three levels of containment.

Fortunately, the ISS is well stocked with clear polyethylene bags. Some are manufactured with double walls; others can be nested to create a second protective layer. A third level of confinement is achieved by keeping the bag near an inlet filter of the ventilation system, which provides suction velocities of 0.5–1.0 m s^{-1}.

Both the American and Russian space programs use double-walled polyethylene bags with heat-sealed edges to hold beverages. Some of the experiments reported here used Russian drink bags as containers. When empty and flat, a Russian drink bag is an irregular rectangle with dimensions about 8.5 × 27 cm. When filled with fluid, its volume is 550 ± 5 cm^3 and its effective thickness is 2.4 cm. Most new drink bags contain dry beverage powder whose free-floating aggregate behavior can be studied by simply inflating the bag with air. A drink bag of sweetened tea contains a commercial tea bag and an average of 10.3 g of loose sugar (sucrose) crystals. The tea bag can be trapped in one end of the drink container with a spring clip to allow study of the sugar alone.

Other experiments were contained in food-overwrap packages, stiff polyethylene bags with heat-sealed seams that form approximately rectangular boxes 24.0 × 28.0 × 12.0 cm in size, with an internal volume of about 11,000 cm^3. A food-overwrap bag offers a chance to study the behavior of particles in a larger volume, with less interaction with the container walls. Two other experiments used standard polyethylene zip-lock bags of two sizes, 800 and 4000 cm^3. A single aqueous experiment used a Costar #3075 polystyrene culture flask with a nominal volume of 250 cm^3 and a measured volume of 266 cm^3.

All of the container materials were dielectrics, which acted as electron scavengers, gaining negative charge through contact friction, and as charge barriers able to retain an induced local charge. These properties may have created an electrostatic environment for the contained particles that differed from a protoplanetary nebula. The containers also kept the particles confined at high density: approximately 10^{-3} g of solids cm^{-3}, versus approximately 10^{-11} g of solids cm^{-3} in a protoplanetary nebula (although local turbulence-driven particle concentrations may have been up to $10^5\times$ higher; Cuzzi et al. 2001). Finally, the containers affected the experiments through particle–wall collisions, although these generally resulted in simple reflections of particle flight paths, suggesting that the walls were dynamically similar to neighboring volumes containing the same mixture of air and particles.

The air in the experiment containers was at cabin temperature (21 °C) and pressure (745–750 mmHg). Its composition was 79% N_2, 20% O_2, and 0.5% CO_2 at 40% relative humidity. For the experiments carried out in air, the stopping distance of the particles was 10–20 m, orders of magnitude larger than the container. This indicates that viscous forces played a minor role in these experiments. For a single trial conducted with μm-scale particles in water, viscosity was a dominant factor.

The first set of experiments was conducted on ISS during Expedition 6 in 2002–2003. It used only materials readily available on the Station. Zip-lock bags, Russian drink bags, and culture flasks served as containers, and salt, sugar, instant coffee, and mica were employed as granular solids. Five conditions were tested: salt (NaCl) crystals 0.5–1.0 mm in size, contained in a polyethylene bag with air at a number density of approximately 10 cm^{-3}; 1–6 mm salt crystals in air with approximately 1 cm^{-3}; 0.5–1.0 mm sugar (sucrose) crystals in air with approximately 40 cm^{-3}; 0.1 mm powdered coffee particles in air with approximately 5000 cm^{-3}; and 5 μm mica flakes in a culture flask of water with approximately 10^8 cm^{-3}. The particles used in these tests were 10^1–$10^4\times$ larger than the approximately 1 μm primary dust particles of a protoplanetary nebula. The materials used are obviously not important in planet formation, but they do represent a crystalline ionic solid, crystalline and noncrystalline organic solids, and a hydrated silicate.

The second set of experiments was conducted in 2008, while Space Shuttle mission STS-126 was docked to the ISS. It investigated the aggregate behavior of chondrules from the L/LL4 chondrite Bjurböle (sample USNM 610). Bjurböle and its chondrules have been very thoroughly studied (e.g., Caffee et al. 1982; Rietmeijer and Mackinnon 1984; Nava 1994; Wasilewski et al. 1995; Kuebler and McSween 1996; Kuebler et al. 1997; Kletetschka et al. 2001). In preparation for flight, the chondrules were disaggregated, washed with absolute ethanol in an ultrasonic cleaner, baked dry in an oven at 120 °C for 3 h, and finally exposed to vacuum for 3 h at

0.1 mmHg pressure and 80 °C. The chondrules were sieved and the 1–2 mm size range selected for study. The mass of the resulting sample was 26.54 g, and the average diameter of the particles was 1.7 mm. Assuming a material density of 3.4 g cm^{-3} (Kuebler et al. 1997) the sample mass corresponds to about 3000 chondrules. The experiment was contained in a Russian drink bag at a number density of about 6 cm^{-3}.

The ISS Expedition 30 (2011–2012) experiments used a wider variety of materials, including the L6 ordinary chondrite Allan Hills A76009 (sample USNM 6285) and the CV3 carbonaceous chondrite Allende (sample USNM 3529,8). Although these meteorites are composed of materials that were important in planet formation, they have undergone physical compaction since they originally accreted (e.g., Beitz et al. 2013). Both of the samples were crushed and sieved, and the largest particles selected for study. For safety reasons, we elected to transport and handle the meteorite particles on a string, from which they were released after they were enclosed in their double-walled experiment bags. This required that we drill a 1 mm hole through the center of each particle. Only 46 particles (42 of Allende, and 4 of ALH A76009, which proved difficult to drill through without fracturing), 4–7 mm in size, were large enough for this operation, which unfortunately limited the quantity and size range of material that could be studied. The meteorite particles were tested in a double food-overwrap bag in air at a number density of 0.004 cm^{-3}.

In addition to the meteorite materials, we tested 2.6 × 3.2 mm spheroidal acrylic beads. Each had a 1.0 mm hole through the center. The sample, contained in a double food-overwrap bag, consisted of about 1200 particles in air at 0.1 cm^{-3}. A similar trial used spheroidal glass beads 1.4 × 2.1 mm in size, each with a 0.84 mm center-drilled hole and a layer of vapor-plated silver to create a thin electrically conductive (resistance <1 Ω) surface layer. The experiment used about 2150 beads in air at a number density of 0.2 cm^{-3} and was contained in a double food-overwrap bag. As with the meteorite fragments, the acrylic and glass beads were transported on strings and released inside the experiment bags.

Expedition 30 retested some of the materials used in Exp. 6 at different number densities. These trials included 0.5–1.0 mm sucrose particles in air at 4 cm^{-3}, and 0.5–1.0 mm NaCl crystals in air at approximately 0.1 cm^{-3}. Another experiment repeated the conditions of the Exp. 6 sucrose experiment, but left the container clipped to the wall where it was gently agitated (amplitude approximately 1 cm, period approximately 2 s) by ventilation air flow and observed over a period of days.

Yet another experiment mixed together two Russian drink bag charges of sugar crystals (20.6 g total), plus the glass beads, acrylic beads, and meteorite pieces from the experiments described above, in a double food-overwrap bag. The particles were suspended in air at a total number density of 4 cm^{-3}.

The final Exp. 30 particle aggregation experiment used water ice, an important constituent of protoplanetary disks. Ice shavings were prepared from a 160 × 80 × 15 mm block of ISS drinking water frozen at −85 °C (compared to approximately −110 °C at the snow line of a protoplanetary nebula) using a precooled grater with 2 mm openings. The resulting ice particles, 1–6 mm in size and about 10^4 in number, were confined in a double food-overwrap bag at a number density of approximately 1 cm^{-3}. The shavings remained frozen for about 10 min before melting. Particles that contacted the walls of the bag melted quickly.

Table 1 summarizes the conditions and outcomes of all the experiments. In the table, a tilde (~) indicates a quantity that was derived indirectly (such as number densities estimated from video imagery) and that therefore has an uncertainty of about a factor of 2. The uncertainty of other quantities is indicated by the stated ranges or the number of significant digits presented.

RESULTS AND DISCUSSION

The trials conducted during Exp. 6 with particles in air yielded counterintuitive and strikingly similar results. In every case, within a few seconds of being thoroughly shaken, the majority of the particles aggregated into 1–5 cm loose fractal structures similar to those reported in comparable experiments (e.g., Marshall et al. 2005) and models (e.g., Okuzumi et al. 2012). Salt, sugar, and coffee all behaved similarly, indicating that the process is not critically dependent on particle composition. The spontaneity, speed, and repeatability of aggregation suggest that it is energetically favorable. Figures 1A and 1B show, respectively, NaCl crystals in air at approximately 10 cm^{-3} immediately after strong shaking, and a few seconds later.

The aggregates formed in these experiments could withstand gentle shaking (approximately 5 cm travel at approximately 1 cycle per second, implying accelerations of a few tens of cm s^{-2}, peak velocities of approximately 10 cm s^{-1} relative to the gas, and a cohesive strength of a few Pa) and survive impacts with the wall of the bag with minor deformation. The clusters broke up when shaken more strongly. These results imply that similar structures could have readily survived gas drag forces in a protoplanetary nebula with approximately 1 Pa pressure and approximately 100 m s^{-1} turbulent velocities (Love and Pettit 2004). In

Table 1. Microgravity particle aggregation experiment conditions and results.

Flight	Material	Size (mm)	Number density (cm^{-3})	Container	Medium	Time scale	Cohesion
Exp 6	NaCl	0.5–1.0	~10	4000 cm^3 zip-lock bag	Air	3 s	Strong
Exp 6	NaCl	1–6	~1	800 cm^3 zip-lock bag	Air	5 s	Strong
Exp 6	Sucrose	0.5–1.0	40	550 cm^3 Russian drink bag	Air	5 s	Strong
Exp 6	Coffee	~0.1	~5000	550 cm^3 Russian drink bag	Air	2 s	Strong
Exp 6	Mica	~0.5 μm	10^8	266 cm^3 culture flask	Water	Days	Weak
STS-126	Chondrules	1–2	6	550 cm^3 Russian drink bag	Air	Days	Very weak
Exp 30	Meteorite[a]	4–7	0.004	11,000 cm^3 food-overwrap bag	Air	Days	None
Exp 30	Acrylic	3	0.1	11,000 cm^3 food-overwrap bag	Air	Days	None
Exp 30	Coated glass	2	0.2	11,000 cm^3 food-overwrap bag	Air	Days	None
Exp 30	Sucrose	0.5–1.0	4	11,000 cm^3 food-overwrap bag	Air	20 s	Strong
Exp 30	Sucrose	0.5–1.0	40	550 cm^3 Russian drink bag	Air	Hours-days (agitated)	Very strong
Exp 30	Mix[b]	0.5–7	4	11,000 cm^3 food-overwrap bag	Air	Hours	Preferential
Exp 30	Ice	1–6	~1	11,000 cm^3 food-overwrap bag	Air	Minutes	Weak

[a]Allende and Allan Hills A76009 meteorite pieces.
[b]Sucrose crystals, acrylic beads, coated glass beads, and Allende and Allan Hills A76009 meteorite pieces.

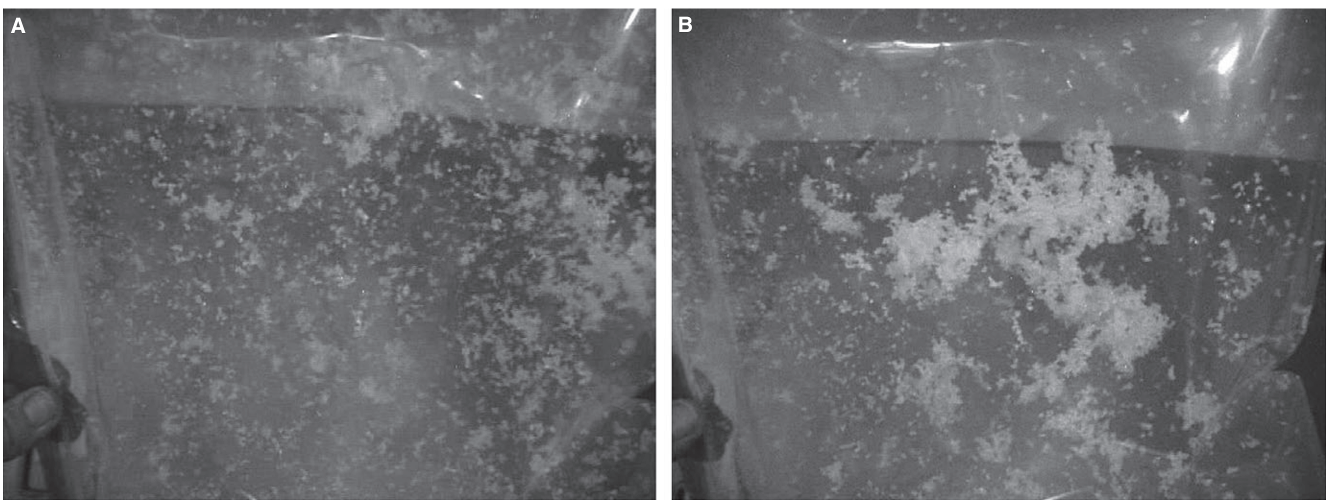

Fig. 1. Salt (NaCl) crystals 0.5–1.0 mm in size, suspended in air with a number density of approximately 10 cm^{-3}. A) Immediately after strong shaking. The field of view is 25 × 20 cm. B) The same experiment a few seconds later.

such an environment, bombardment by smaller particles, which are better coupled to the gas, might pose a threat, but the assemblages' porous nature would have made them resistant to impact damage (e.g., Love et al. 1993) and perhaps better able to accrete some of the projectiles (e.g., Seizinger and Kley 2013). The Exp. 30 experiment with sucrose in a bag left to wave in the ventilator airflow for days produced a population of compacted, cm-sized spheroidal aggregates, as illustrated in Fig. 2. These were even more durable than their unconsolidated precursors, needing several seconds of vigorous shaking to disrupt.

In a real protoplanetary nebula, the average number density of particles is likely to have been approximately 10^8 times smaller than in these experiments (e.g., Cuzzi et al. 2001; Cuzzi and Weidenschilling 2006; Weidenschilling 2010). If particles interact only through contact forces, then aggregates should grow on a time scale inversely proportional to the particle number density (e.g., Blum 2006). At low nebular densities, scaling from these experiments implies aggregation times of 1–10 yr. The process may be accelerated by local turbulent concentrations (Cuzzi et al. 2001).

Our experiments suggest, however, that the assumption of simple inverse density scaling may be incorrect. Comparing the Exp. 6 trials with NaCl at 10 and 1 cm^{-3}, and the Exp. 6 and Exp. 30 trials with

Fig. 2. Durable cm-sized spheroids of sugar (sucrose) formed from loose 0.5–1.0 mm crystals in air at a number density of 40 cm^{-3}. The container, a Russian drink bag, was placed for days in the airflow from a ventilator, which gently, but continuously, agitated the bag. The field of view is 11 × 8 cm. A scale ruler is partially visible in the upper left corner of the image.

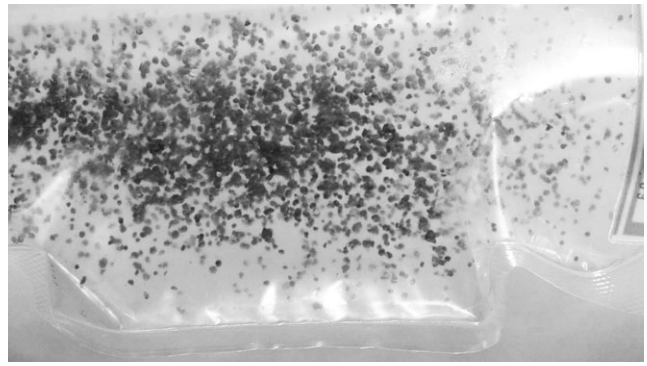

Fig. 3. Bjurböle chondrules 1–2 mm in size, contained in a Russian drink bag. Note the lack of strong clumping. The field of view is 14 × 8 cm.

sucrose at 40 and 4 cm^{-3}, shows that the aggregation time scale in these systems increases by a factor of only 2–4 with a 10-fold decrease in particle number density. Even allowing for the different material, the trial using coffee particles at approximately 5000 cm^{-3} had an aggregation time comparable to those observed at number densities 100–1000 times smaller. On the basis of these results, particle aggregation in a real nebula seems likely to be more efficient than predicted by the inverse of the number density. From this, it follows that forces other than those related to direct surface contact must control the process, as also noted by Marshall and Cuzzi (2001) and Marshall et al. (2005), who suggested electrostatics as a candidate mechanism allowing particles to interact at distances greater than their physical sizes (see also Ivlev et al. 2002; Matthews et al. 2013). Electrostatic aggregation is not based on surface contact forces, but on "regions of influence" (as defined by particle charges and random velocities) within which all neighboring particles are quickly accreted.

Several observations from our experiments corroborate the electrostatic model. First, video documentation of the experiments showed cases of individual particles abruptly accelerating and reorienting as they approached growing aggregates, and aggregates forcibly ejecting particles after gently gathering other particles elsewhere on their surfaces. Second, scratching the bag with a fingernail produced an area that visibly attracted particles. Third, touching the bag with a makeshift Van de Graaff generator creating potentials of tens of kV produced vigorous motion of both aggregates and individual particles away from the contact point.

The experiment with Bjurböle chondrules investigated the aggregate behavior of a material important in solar system formation. It yielded unexpected results. Once shaken up, the chondrules showed very little cohesion (Fig. 3), even when left undisturbed for days. Occasional transient aggregates of 10–20 chondrules formed when relative speeds were approximately 0.5 cm s^{-1} or less. Any disturbance broke up the clumps. Similar weak cohesion of chondrules has been noted by Beitz et al. (2012). The well-characterized magnetism of Bjurböle chondrules (e.g., Nava 1994; Wasilewski et al. 1995; Kletetschka et al. 2001) appears to be too small to affect clumping, although it is possible that sample preparation, which included heating to 120 °C, could have disturbed the native magnetism (e.g., Kletetschka et al. 2001).

Although the chondrules barely cohered with one another, scratching the surface of the bag with a fingernail created a spot that weakly, but visibly, attracted them. This behavior suggests that chondrules do respond to electrostatic forces. But their larger size, stony composition, spheroidal shape, smooth surface, or some combination of those factors appears to inhibit the electrostatic process (possibly tribocharging, e.g., Marshall and Cuzzi 2001; Marshall et al. 2005) that dominated the Exp. 6 experiments. Particle size alone probably does not account for the difference, because the Exp. 6 experiments with NaCl crystals 1–6 mm in size produced aggregates almost as quickly as trials with 0.5–1.0 mm NaCl crystals. Composition also seems an unlikely culprit, given the similar behavior of the different compositions tested in Exp. 6.

The Exp. 30 experiments with meteorite fragments, with acrylic beads, and with coated glass beads showed even less cohesive behavior. In all three tests, no

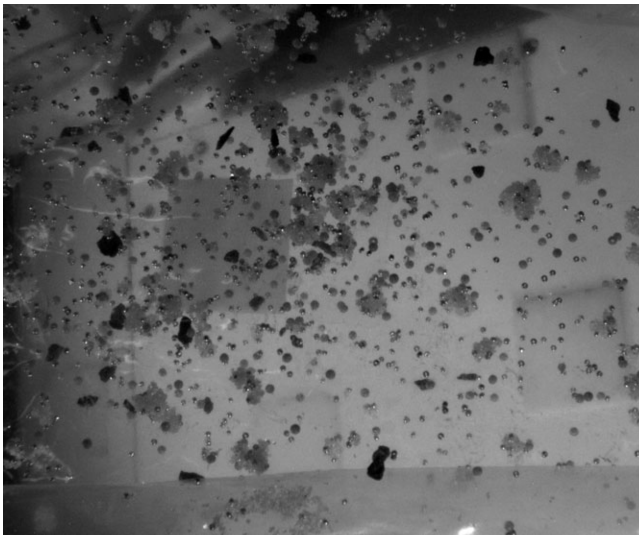

Fig. 4. Aggregates and individual particles of sucrose, coated glass and acrylic beads, and Allende and Allan Hills A76009 meteorite fragments in a food-overwrap bag allowed to wave gently in ventilation airflow for several hours. The resulting clumps are preferentially dominated by sugar, with other phases included only incidentally. The field of view is 30 × 20 cm.

aggregates formed. Although these experiments had lower number densities than the Exp. 6 trials, the weak dependence on number density observed in those tests suggests that number density cannot by itself explain the lack of clumping. As suggested above, particle size alone also is unlikely to account for the difference. Both dielectric (acrylic) and conductive (coated glass) particles showed the same behavior.

The mixed experiment, which combined the meteorite pieces, acrylic beads, and coated glass beads along with 20.6 g of sucrose, did produce aggregates over a period of days with gentle airflow agitation of the container. Figure 4 illustrates the results. The clumps were dominated by sucrose crystals, apparently including other phases only incidentally. Possibly, the flat faces or sharp corners of the sugar crystals enhance their mutual electrostatic attraction, a hypothesis that could also explain the observed weak cohesion of rounded chondrules and beads. Alternatively, organics such as sucrose (and the coffee tested during Exp. 6) may be stickier than the other materials tested (e.g., Kudo et al. 2002). Regardless of the physical mechanism, the observed preferential clumping behavior indicates that phases that do not readily cluster together can still be incorporated into assemblages of other, more cohesive, materials (as also reported by Beitz et al. 2012), albeit with potentially strong selection effects. More importantly, it also suggests that the composition of growing planetesimals may not be representative of the local solid materials.

The experiment with ice showed some weak aggregation, which was difficult to document because of condensation and larger water droplets accumulating on the inside of the bag. It was not possible to determine whether the observed clumping was attributable to a thin liquid water layer on the ice particles as they approached room temperature, or to some degree of electrostatic charge. The action of grating the ice might be expected to produce some charge on the resulting particles, but in this simple experiment, the charge could not be measured or confirmed.

Finally, the experiment with mica flakes suspended in water for several days produced obvious fractal aggregates of particles. The conditions in this trial were clearly not analogous to a protoplanetary nebula, but the experiment is interesting in comparison with the others. Despite the smaller particle size, the greater density and viscosity of the surrounding fluid, the longer time scale, and the probably dissimilar (i.e., not electrostatic) clumping mechanism, the same general behavior was observed. This suggests that the model systems reported here are a robust analog for particle aggregation across a wide range of conditions, possibly including those in protoplanetary nebulae. Weitz (2014) presents further studies of fluid-particle systems in microgravity.

CONCLUSION

In this report, we described a series of experiments conducted on the International Space Station that investigated the aggregate behavior of millimeter and submillimeter particles in microgravity. The most important observation is that submillimeter particles rapidly and spontaneously form clusters. The aggregates can be strong enough to survive turbulence in a protoplanetary nebula. Although these simple experiments did not formally separate the parameters, there appears to be no simple relationship between the speed and strength of aggregation and the variables of number density, composition, shape, and surface roughness. Generally, larger particles appear to aggregate less strongly than smaller ones, as expected for a mechanism that plays surface-dominated electrostatic forces against mass-proportional inertial ones. We found only a weak dependence on particle number density. There seems to be little dependence on composition. Round, smooth particles aggregate weakly or not at all. In mixtures of particles, certain phases clump more strongly than others, creating not-yet-understood selection effects that control the composition of the aggregates. These effects may also operate in protoplanetary nebulae, causing systematic differences between the composition of growing planetesimals and that of the available solids.

Although these experiments lacked formal controls and measurements to identify the clumping mechanism, our observations are consistent with electrostatics. (Investigators limited to 1 g environments can observe the power of electrostatics in systems of small particles by opening up a beanbag chair.) A full understanding of the problem will have to take into account the complex interplay among electrostatic, inertial, and viscous forces.

Applying these results to protoplanetary nebulae may be valuable in improving our understanding of planet formation, but doing so will be challenging. First, although we used consistent materials that were not electrically active, it was not possible to quantify or eliminate the effect of the container. Second, only a few of our trials used particles with compositions relevant for planet formation. Third, real protoplanetary nebulae, which contain radioactive species and are bombarded by cosmic rays, may have regions with enough ionization to affect triboelectric charging of solid particles. A truly realistic experimental treatment of protoplanetary dust growth would have to address all of these factors while matching the conditions of gas pressure, temperature, composition, electrical charging, and turbulence present in a real nebula. Such an investigation would be complicated and expensive.

Despite the shortcomings of our investigation, we note that scientifically relevant results can be obtained in simple space experiments, which can be largely free from gravity and viscosity and which can easily run for days. The key ingredient is not expensive equipment, but observers interested enough to notice and document novel effects in this special environment.

In the future, we hope to try more formal and sophisticated experiments using more realistic materials. We also hope to employ a more realistic particle size distribution, including the small size fraction, which these experiments suggest is important in microgravity aggregation. Further work would formally control and separate the effects of particle size, number density, composition, shape, and surface roughness. It may also be possible to do experiments at reduced gas pressures, further improving the similarity to protoplanetary nebula conditions.

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